Case Study of Groundwater Flow Within the Commodore Mine Complex and Implications for Source Control[1]

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The Commodore mine complex, located north of the town of Creede in southern Colorado, was developed along the Amethyst Vein in the early 1890's in search of silver ore. Discoveries of rich silver ore and associated base metals enabled periodic mining throughout the early 20th century until the late 1970's. Now, over 250 gallons per minute of metal laden waters flow from the mine workings through the Nelson Tunnel polluting three miles of Willow Creek and eventually spilling into the Rio Grande River. Local stakeholders in cooperation with both state and federal agencies are seeking to understand the groundwater hydrology of the mine complex in hopes of implementing source control as a treatment method. Various hypotheses regarding recharge and pathways for groundwater flow within the mine have been proposed and are currently being confirmed through historic research, tracer studies, geochemical and isotopic water analysis and underground investigations.

Additional Key Words: mine drainage,

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Introduction

Numerous coal and non-coal minesites throughout the United States are plagued with perpetual acidic and heavy metal laden mine drainage that negatively impact the environmental quality of many surface waters. Often, construction of large scale treatment facilities to capture and treat contaminated water is not physically or financially feasible, thus resulting in the need to explore other options such as source control. Source control techniques utilize methods of flow prevention like grouting and bulkheading to reduce or eliminate mine water discharge. Complete elimination of discharge is rarely possible, but the reduction in volume or metal concentrations may enable the use of cheaper treatment alternatives. To effectively implement source control on any minesite, comprehensive characterization of the regional and local factors affecting groundwater movement and contamination within the mine must be conducted.

The Commodore Mine in Creede, Colorado has afforded a unique opportunity to explore the possibility of source control implementation. Beginning in 2000, a local stakeholders group, the Willow Creek Reclamation Committee (WCRC) in cooperation with numerous federal and state agencies including the Colorado Division of Reclamation, Mining and Safety (CDRMS) began exploring source control as a possible solution for metal laden water discharging from the Nelson Tunnel into Willow Creek, and eventually the Rio Grande River. The project goal is to utilize source control to eliminate the need for perpetual treatment or reduce the costs associated with treatment. A variety of tools are being used to determine the feasibility of source control:

a) Historic research of water flow within the mine complex,
b) Acquisition of mine related information like mapping and geology,
c) Regional geologic and hydrologic research,
d) Underground mapping and surveying,
e) Tracer study,
f) Geochemical and isotopic water analysis,
g) Continued monitoring of hydrologic parameters like flow and water levels,
h) Pilot dewatering project.

This paper will present the relevant context for the Commodore Mine Complex and summarize the work completed, underway and proposed relating to the characterization of groundwater movement within the mine, and discuss the implications for source control.

Background

Location and Geographic Setting

The Commodore Mine complex is located near the center of the San Juan Mountains in southern Colorado. Creede, is the closest town to the mine, located two miles to the south as shown in Figure 1. The population of Creede is less than 500 year round residents, although the area sees a substantial influx of summer tourism related to camping, four-wheeling, fishing and various other outdoor activities. Another large tourism draw for the area is the rich and colorful mining history, of which the Commodore Mine played a central role.

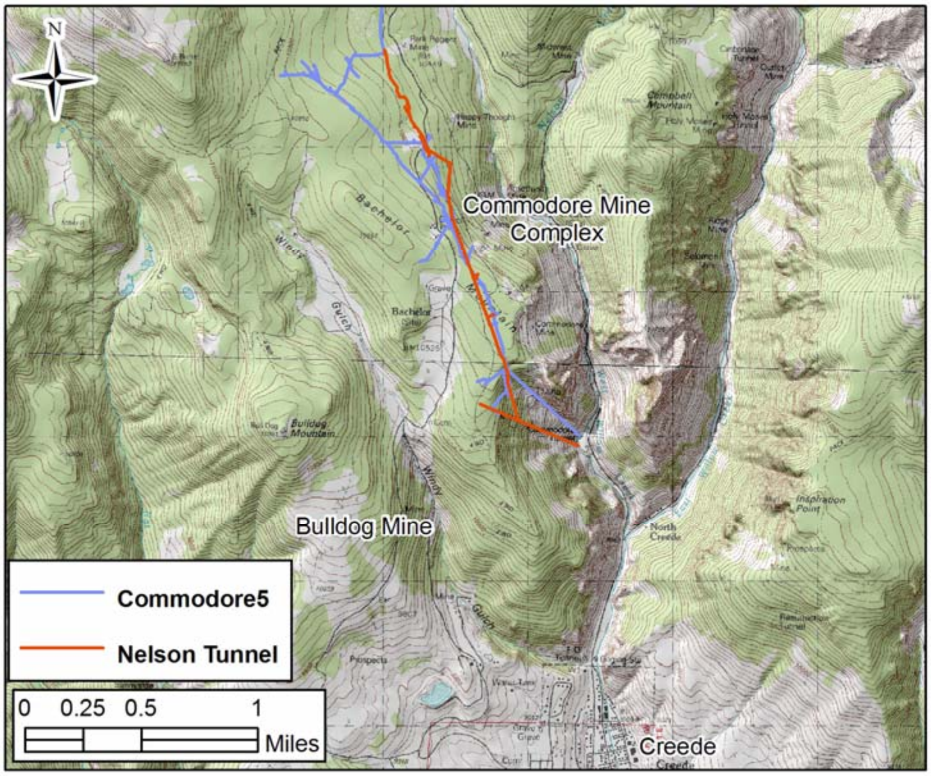

Figure 1. Location Map.

The topography is generally very steep and rugged. Willow Creek, a high gradient mountain stream flows through the Commodore minesite, the town of Creede and eventually into the Rio Grande River whose headwaters are located not far from the mine. As shown by ongoing water quality characterizations of Willow Creek by the WCRC the Nelson Tunnel drainage, draining the Commodore Mine Complex and averaging 250 gpm, remains the single largest heavy metals contributor to the watershed. Water quality results from water collected at the Nelson Tunnel Portal are shown below in Table 1.

Site	pH	Cond. (uS/cm)	AL_D (ug/L)	CD_D (ug/L)	CU_D (ug/L)	FE_D (ug/L)	MN_D (ug/L)	ZN_D (ug/L)
Nelson Adit	4.19	1098	160.8	35.7	26.5	148	12110	63740

Table 1. Dissolved metals in Nelson Tunnel drainage (6/6/03).

Brief History

Exploration and prospecting of the mountains surrounding the town of Creede had humble beginnings in the early 1880's. Prospectors Mackenzie and Bennett first staked claims along the Alpha Corsair vein in 1883, but it wasn't until the discovery of rich silver ore along the Holy Moses vein by Nicholas Creede in 1889 that mining within the district caught fire. The 1890's saw extensive development of silver ore along the three major vein systems, the Alpha-Corsair, the Solomon-Holy Moses and the Amethyst. The majority of silver production came from at least seven separate mines, mostly shafts, allocated along the Amethyst vein including the Bachelor, Commodore, Del Monte, Last Chance, Amethyst, Happy Thought and Park Regent. The need for easier and cheaper haulage, and adequate drainage, resulted in the organization of competing tunnel companies, the Nelson Tunnel Co. and the Commodore Mine during the 1890's. The Nelson Tunnel was driven approximately 2100 feet into the mountain to access the amethyst vein, and was eventually extended an additional 11,000 feet along the vein as the Wooster Tunnel and the Humphreys Tunnel to access the base of numerous shafts. Both haulage and drainage were provided for the above mentioned mines by the Nelson Tunnel, which allowed for extensive mining of the amethyst vein across nearly 1400 vertical feet. The Commodore Mine drove the Commodore 5 level adit 2200 feet to the vein and approximately 45 feet above the Nelson Tunnel to provide alternative access to workings along the amethyst vein (Emmons & Larsen, 1923). Eventually, the Commodore 5 level was driven to access the same workings as the Nelson Tunnel.

Mining within the Creede district continued periodically through the 1960's mostly along the amethyst vein until discovery of the Bulldog mine west of the amethyst in the late 1960's. Mining ceased along the amethyst vein in 1976, but continued at the Bulldog mine until 1989. The estimated production of the Creede mining district through 1999 was about 85 million ounces of silver; 155,000 ounces of gold; 5,480 tons of copper; 160,000 tons of lead; and 50,000 tons of zinc (Nelson, 1989).

Geology

Regional Geology

The Creede mining district occupies a geologically complex region of Tertiary aged volcanic activity. The majority of rocks exposed regionally throughout the San Juan Mountains can be closely tied to the formation and eruption of at least 17 separate volcanic calderas shown in Figure 2 (Steven and Eaton, 1975). Eruption and formation of the numerous calderas deposited thick sequences of ash flow tuffs across hundreds of square miles. The collapse and eventual resurgence of many of the calderas resulted in substantial fracturing and faulting that provided pathways for the migration of ore forming solutions. Magma associated with caldera development was generally responsible for heating of circulating meteoric waters which carried metal rich solutions towards the surface for eventual precipitation. Within the Creede district, ore deposition appears linked to post formational processes of the Creede caldera.

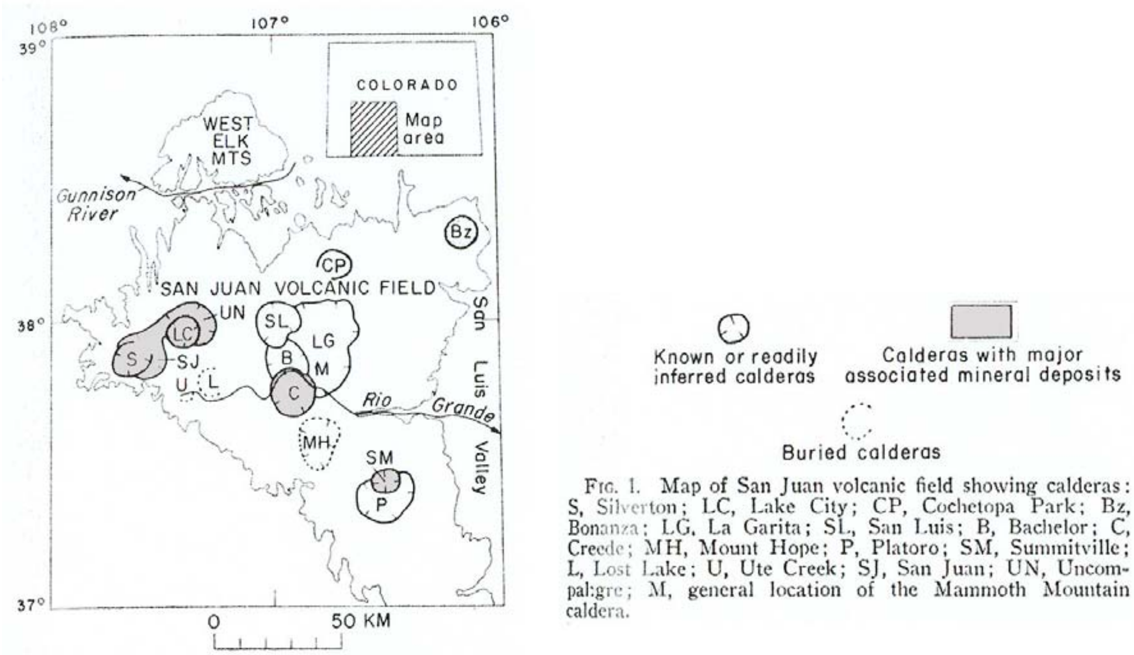

Figure 2. Calderas of the San Juan Mountains, Colorado (reprinted from Steven and Eaton, 1975).

The Creede caldera, an eight mile wide collapse feature formed by the eruption of the Snowshoe Mountain Tuff, was the final eruption within the central San Juan mountains resulting in widespread ash flow sheeting. Following eruption of the Creede caldera, resurging magma within the caldera boundary led to a set of north trending distentional fractures just north of the caldera's margin as shown in Figures 3 and 4. This distentional fracturing formed what is now referred to as the Creede Graben, and is composed of four major fault systems, the Alpha-Corsair, Bulldog Mountain, Amethyst, and Solomon-Holy Moses. A moat developed between the resurged dome and the collapsed caldera walls and began to fill with alluvial and lacustrine deposits generated from the surrounding volcanic highlands. These interbedded deposits are referred to as the Creede Formation, and may have played an important role in eventual ore formation within the Creede Graben. Following deposition of the Creede Formation, magma resurged along the northern caldera margin reactivating faults within the Creede Graben, and is postulated as the driving force behind ore deposition within the Creede District (Steven and Eaton, 1975). Mineralization within the Creede District appears to have taken place close to the surface and along recently active distentional faults formed by the intrusion of magma (Steven and Eaton, 1975). Bethke and Rye (1979) suggested that fluid inclusion studies indicate meteoric water from multiple sources acted as the medium for ore transportation. They proposed a meteoric source from within the moat formed by the Creede caldera, and a source north of the district along the continental divide. If a source for ore formation existed along the continental divide in the past, then the potential pathway is likely in existence today.

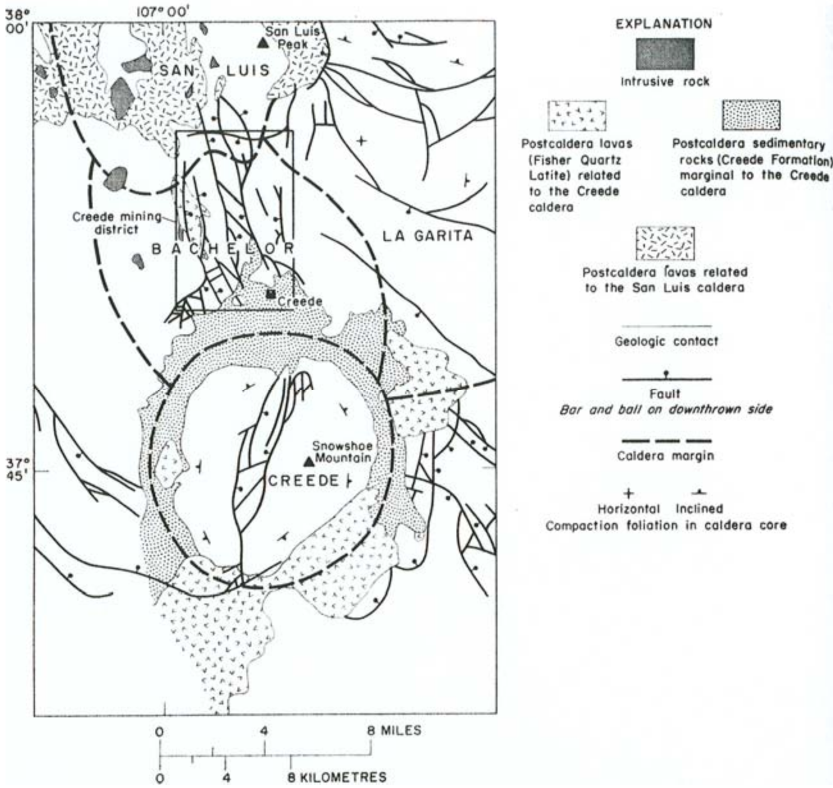

Figure 3. Creede District geology (reprinted from Steven and Eaton, 1975).

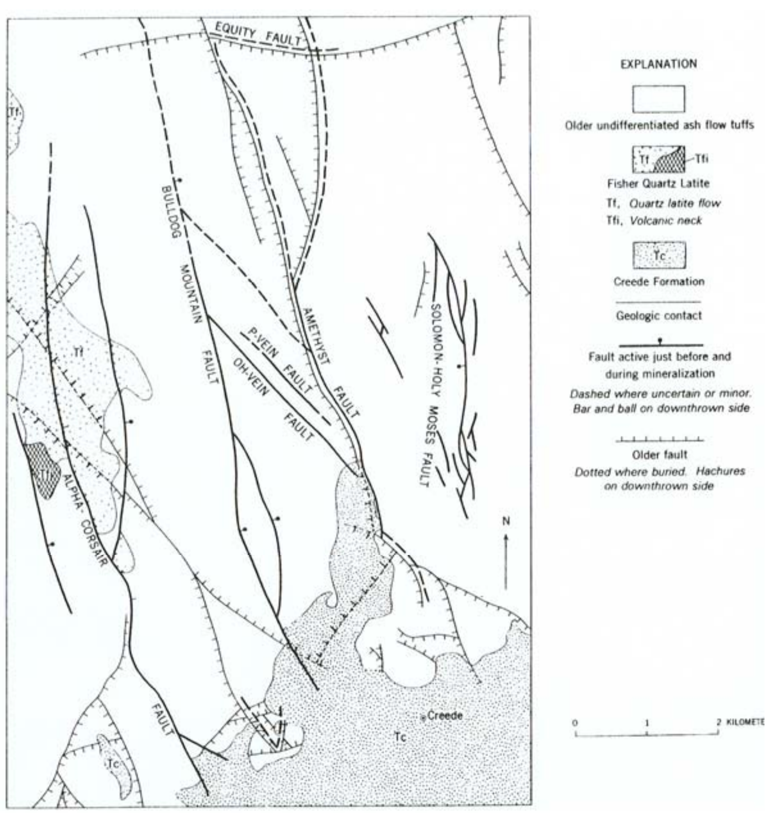

Figure 4. Creede District faults (reprinted from Bethke and Rye, 1979).

Geology of the Commodore Mine Complex

The Commodore Mine complex worked the Amethyst fault system, a combination of veins varying less than inches to more than 15 feet in width that strike N 20º W and dip to the southwest between 55º and 80º. The Amethyst fault is the eastern complement to the Bulldog Fault with both bounding one of the inner keystone blocks of the Creede Graben. The majority of the Amethyst fault has displaced members of the Bachelor Mountain rhyolite, with the Willow Creek member forming the footwall and the Campbell Mountain member forming the hanging wall. Towards the southern and upper end of the Commodore Mine the Creede formation is also displaced by the fault.

Two additional veins were also worked through the Commodore Mine, the OH-vein and the P-vein. The OH-vein is a nearly vertical vein striking northwest and possibly extending to the Bulldog Mountain fault. Numerous open vugs with extensive euhedral crystal growth are evident along both OH and P veins on the Commodore 5 level. The upward migration of hydrothermal fluids appears to be responsible for the deposition of ore along the vein. Ore fluids migrated upward and cooled, depositing sulfide minerals including sphalerite, galena, chalcopyrite and pyrite towards the surface. An alteration cap formed by the circulation of boiling hydrothermal fluids through poorly cemented tuffs near the surface restricting the upward migration of ore fluids along much of the vein. The most productive portions of the vein were in areas that lacked the alteration cap, and were exposed to cooler near surface waters resulting in more rapid deposition of metals from solution (Robinson and Norman, 1984). Over time an oxidized zone along the vein developed within approximately 300 feet of the surface as shown in Figure 5. Much of the silver ore was concentrated near the base of the oxidized zone as native silver and silver chlorides. Within the lower sections of the vein, silver was mined from argentiferous galena and minor argentite. Below the Nelson Tunnel level, exploration indicated unprofitable sulphide ore.

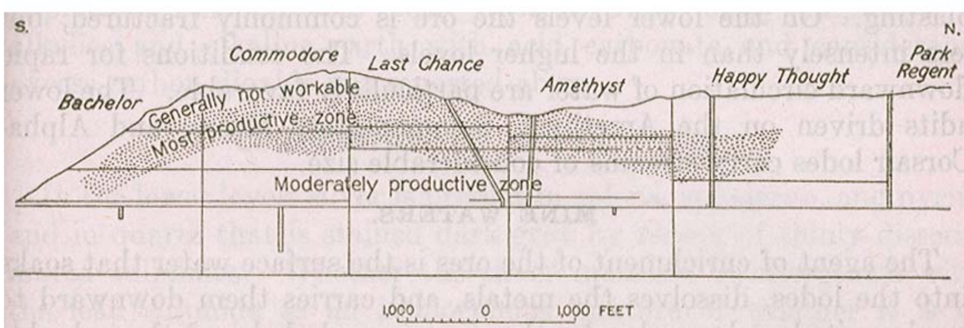

Figure 5. Vertical project of the Amethyst Lode (reprinted from Emmons and Larsen, 1923).

Commodore Mine Complex

The Commodore Mine complex is actually a number of separate mines, mostly shafts that sunk workings along the Amethyst vein system and were eventually all joined through the Nelson Tunnel and Commodore 5 level. The mines from south to north along the Amethyst vein system include: Bachelor Mine, Commodore Mine, Last Chance-New York-Del Monte, Amethyst, Happy Thought and Park Regent. Most of the shafts developed 12 or more levels along a nearly 1400 foot vertical section of the Amethyst Vein. The Commodore and Amethyst mines also developed workings along the OH and P veins. Nearly 3 continuous miles of the Amethyst vein were worked by various mines.

The lowest entry into the mine complex is the Nelson Tunnel. Approximately 45 feet above the Nelson Tunnel is the Commodore 5 level. These two levels converge due to the steeper Nelson Tunnel gradient over two miles from their respective portals near the Park Regent shaft. Workings extend an additional few thousand feet farther north along the Amethyst vein from the Park Regent shaft before dying off. The OH vein has been extensively worked from its junction with the Amethyst vein northwestward. The P vein has also been worked, but not as extensively as the Amethyst or OH veins. Additional exploration work was conducted below the Nelson Tunnel level at the Bachelor shaft, Commodore shaft and Berkshire shaft. Exploratory drifts were driven along the Amethyst vein around 350 feet below the Nelson Tunnel.

Underground Investigations

Rehabilitation and Safety Work

To adequately establish the possibility of source control, underground investigation of the workings and water movement through the mine became a crucial component. Since mining and exploration took place during the 1970's access to the Commodore Mine complex could be achieved both on the Commodore 5 and Amethyst 5 levels. Little was known regarding the condition of the workings underground or of the exact water flow pathways except for varying accounts by locals. Initial investigations began in 2001 by members of the WCRC and CDRMS.

The preliminary survey of the workings revealed a number of locations that required rehabilitation and stabilization to safely perform future water quality monitoring. Two local miners were hired to perform the necessary underground work. The locations where safety work was required are shown on Figure 7**.** Air doors were installed at locations 1 and 2, which successfully prevents ice buildup in the mine entry and allows for year round access to the workings. Stabilization and cleanup work was conducted at many locations including: Areas 3, 4, 6, 7, 9, 11, 12, 14, 15, 18, 20, and 21. The stabilization work required at the above locations involved the installation of new timbers, stulls, cribbing and lagging to support unstable workings and prevent potential roof fall in the future. Additionally, a substantial amount of collapsed material, muck, was removed from the main haulage way to provide easy passage by foot or rail.

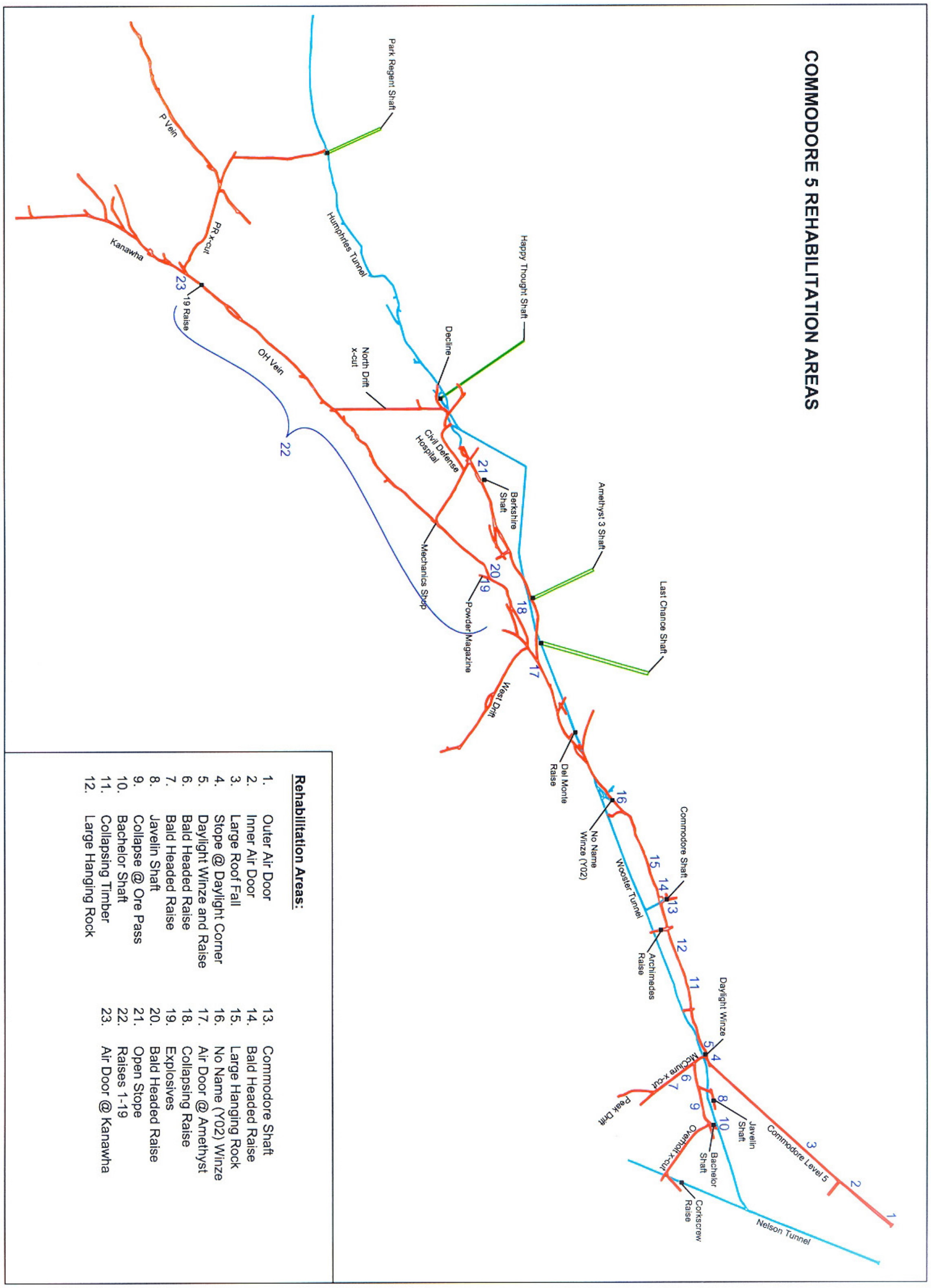

Figure 7. Commodore rehabilitation areas.

Additional rehabilitation work involved the improvement of airflow to the northern workings of the mine. Airflow was redirected by the improvement of air doors at the Amethyst Shaft cut-off, and at Kanawha (Locations 17 & 23). The loss of airflow to upper workings was mitigated through the rehabilitation of air stoppings at numerous raises along the OH vein on the Commodore 5 Level (Location 22).

A substantial portion of the rehabilitation work involved improvement of access to the Nelson Tunnel wherever possible. Five access points from the Commodore 5 Level to the Nelson Tunnel where rehabilitated such that water level measurements and samples of the Nelson Tunnel could be safely taken. Ladders and landings were installed at the Bachelor Shaft, Commodore Shaft, Javelin Winze, Daylight Winze and Noname Winze allowing safe access to the Nelson Tunnel Level (Locations 10,13,8,5 and 16 respectively).


Figure 8. Bachelor Shaft before rehab.


Figure 9. Bachelor Shaft after rehab.

Throughout the work listed above, the mine rail was rehabilitated in hopes of allowing access by rail at some point in the future. By May 2003, rail access was established from the Commodore 5 Level portal to the Nelson Tunnel junction at the Park Regent Shaft. A locomotive, mantrip and timber car were constructed that allowed for better haulage and access to the workings.

The discovery of a substantial amount of undetonated explosives in a powder magazine (Location 19) within the mine became a top safety concern. By May 2003, all safety and rehab work was completed allowing for the safe removal of explosives from the powder magazines. CDRMS was asked by the WCRC to develop and implement an explosives removal plan. Initial investigations of the explosives magazine indicated that approximately 40 cases of Tovex type explosive were present. Additional investigations throughout the mine resulted in the discovery of numerous undetonated nitroglycerine (nitro) type explosives in the Kanawha portion of the mine and at the base of the Amethyst 3 Shaft, and the discovery of undetonated blasting caps at P2 South. Numerous explosives experts along with both state and federal agencies, including Alcohol, Tobacco and Firearms (ATF), Mine Safety and Health Administration (MSHA) and Colorado Department of Public Health and Safety (CDPHE), were consulted regarding safe handling and disposal of the explosives. Finally, a plan was developed involving transportation of all explosives in the magazine to the Trapper Mine in northwest Colorado, and subsequent detonation (if possible) in conjunction with current mining operations. It was also decided that all nitro type explosives and blasting caps were too dangerous to transport and should be detonated in place and rendered harmless. A bomb technician expert and former miner was hired to assist with detonation and transportation of the explosives.

Sufficient mapping of the mine workings was available such that no additional mapping was necessary, but a surveyor was hired to establish vertical control within the mine. Over thirty elevation spads were set throughout the Commodore 5 level to facilitate future water level measurements within the Nelson Tunnel if necessary. Also, a hip chain was used to establish horizontal distances to those spads, and other crucial locations within the mine.

<u>Mine Working Hydrology</u>

One key component of the first underground investigations was the establishment of water quality monitoring points that could be used to adequately characterize hydrologic conditions existing within the mine. A list of the water quality sampling sites is shown in Figure 10. Of utmost importance were possible access points to the Nelson Tunnel level, since that level appeared to be the main conduit of water flow through the mine workings.

One theory regarding water sources within the mine is that surficial water is flowing down the shafts and into the lower workings and out the Nelson Tunnel. The rehabilitation and safety work allowed for access to the base of the Amethyst shaft, Last Chance Shaft and Park Regent Shaft. Minor amounts of water, less than 10 gpm, were observed flowing down both the Amethyst and Park Regent shafts. The base of Last Chance Shaft was completely collapsed, and no water flow was discernable. Very minor amounts of water flow were also observed at Corkscrew Raise, 44 Raise, and a section of the Commodore 5 level between 44 Raise and Noname Winze. Access to the base of the Happy Thought Shaft is impossible due to the flooded condition of the Nelson Tunnel near the base of the shaft. Additional water does appear to be entering the mine workings from the McClure crosscut, but at a flow rate of <10 gpm its impact is limited. Based on current underground observations, it is unlikely that migration of surficial water along the shafts or raises can account for the discharge seen at the Nelson Portal.

The Nelson Tunnel level can be accessed through both the Bachelor Shaft, Noname Winze and near the Park Regent Shaft. Investigations conducted below the Bachelor Shaft on the Nelson Tunnel level observed a substantial amount of impounded water that prevented access to the Nelson Tunnel below the junction with the Wooster Tunnel. A large stope collapse apparently impounding water was also observed along the Nelson just above the Bachelor Shaft. This collapse prevented further exploration upstream of the Bachelor Shaft. A four inch cutthroat flume was installed in the Nelson at the Bachelor Shaft to facilitate accurate flow measurements in the future. Observations

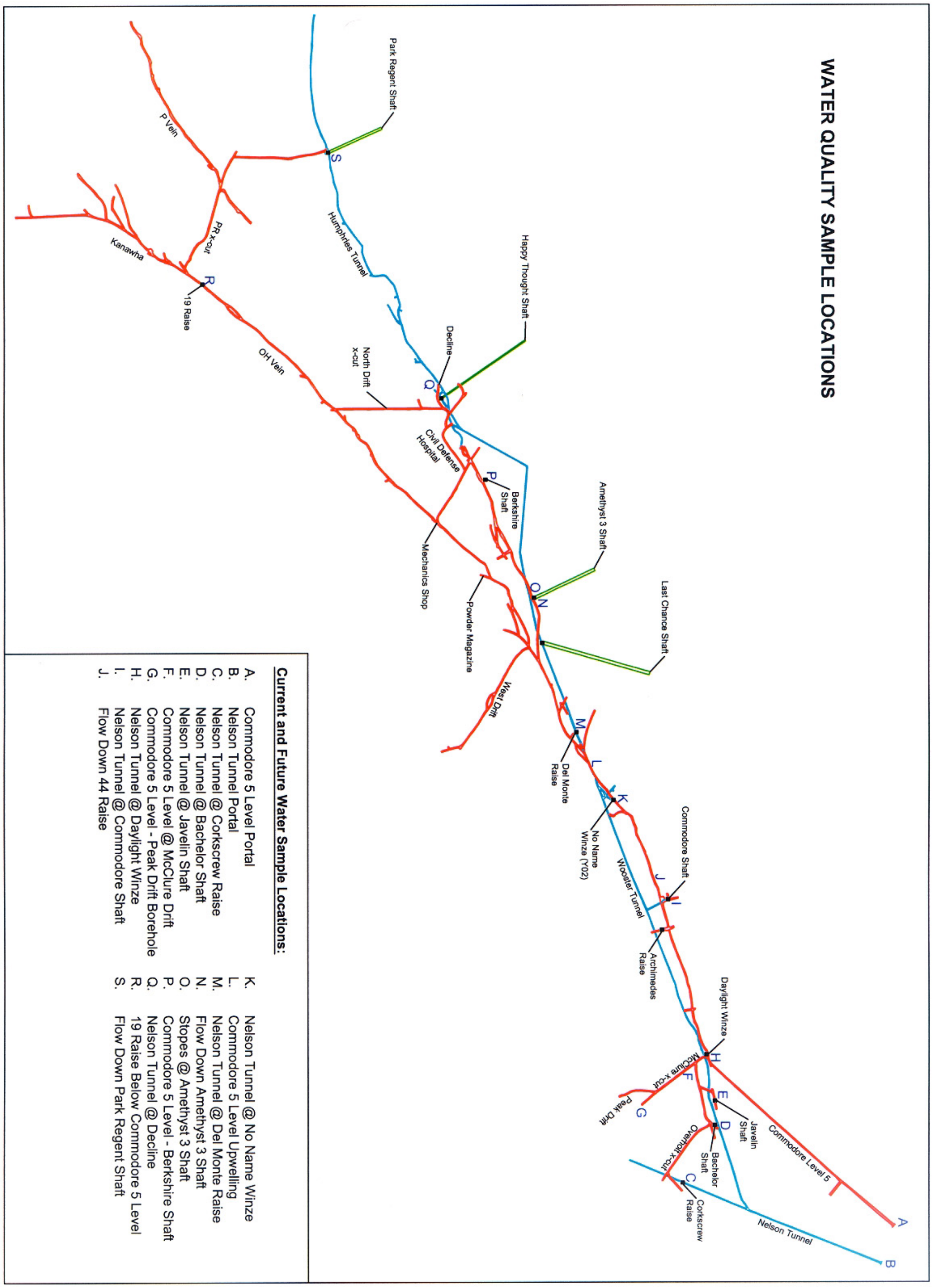

Figure 10. Water quality monitoring points.

of the Nelson Tunnel level at Noname Winze indicated similar conditions to those encountered at the Bachelor Shaft. Water was pooled to an elevation of nearly three feet at Noname Winze, and eventually deepened downstream all the way to the back. Upstream from Noname Winze, water was observed flowing from the top of a large collapse. A flume was used to gage discharge at that location. Both the Commodore 5 level and the Nelson Tunnel (also known as the Humphreys Tunnel) join near the Park Regent Shaft, allowing for access down the Nelson Tunnel level. No flowing or pooled water was observed on the Nelson Tunnel level upstream or in the vicinity of the Park Regent Shaft. Access downstream of the Park Regent Shaft is only possible for a few hundred feet due to a collapsed stope. Observations of the Nelson Tunnel at Javelin Winze, Daylight Corner Winze, Commodore Shaft, Berkshire Shaft and Hospital Decline indicate pooled water above the elevation of the tunnel back.

Water level data collected initially during 2002 and confirmed to date, indicate a series of collapses in the Nelson Tunnel resulting in the formation of at least two major mine pools, shown graphically in Figures 11 and 12. One mine pool appears to extend from the Hospital Decline through the Berkshire Shaft and OH-Amethyst junction to within 500 ft of Noname Winze. The other mine pool extends from that point to a collapse just north of the Bachelor Shaft. These two collapses explain the various flooded portions of the Nelson Tunnel. Additional collapses may be present within the major mine pools, but they don't seem to affect the various water levels within those mine pools. One of the largest remaining unknowns is the collapse sequence from the Nelson Tunnel portal to the Bachelor Shaft. Discussions with former employees of the mine indicate a complex pattern of poor rock conditions resulting in the possibility of numerous collapses along that portion of the mine.

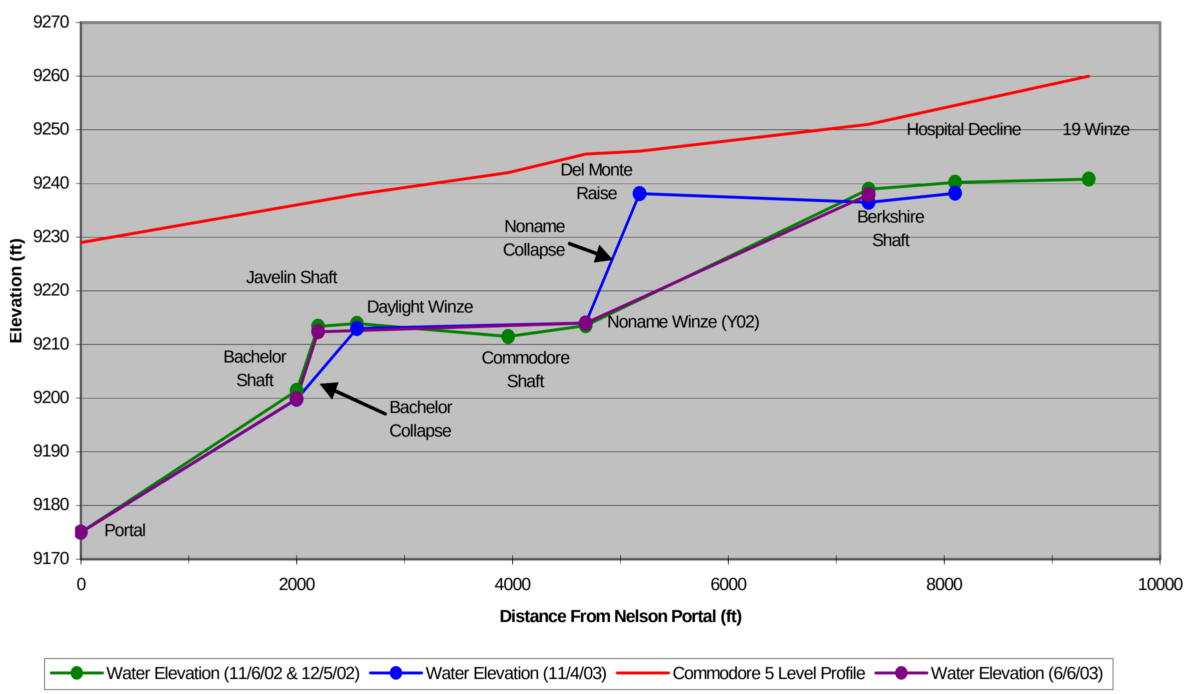

Figure 11. Mine pool elevations relative to Commodore 5 level.

Historical observations and discharge measurements of water flow within the mine workings provide a well documented account of hydrologic conditions in existence during mining. In the early 1890's water was encountered within 200 feet of the surface as shafts were sunk along the Amethyst Vein. As shafts were driven deeper the amount of water needing to be pumped and the costs associated with dewatering increased substantially. During the development of the Nelson Tunnel, historic accounts indicate that large quantities of water were encountered near the base of the Last Chance and Amethyst shafts. Exploratory work conducted from the Berkshire shaft below the Nelson Tunnel from 1917-1920 encountered discharge from the drifts at nearly 1300 gpm. Documents filed in water court by mine owners indicated up to 19 cubic feet per second (cfs) discharge from the working face of the Nelson Tunnel near the Amethyst shaft. A subsequent report by Hodges, 1902, indicated discharge from the Nelson Portal at approximately 3,000 gpm, while in 1965 Meeves and Darnell reported a "moderate" flow. During operation of the Bulldog Mine, adjacent to the Commodore Mine complex, discharge from the Nelson Tunnel was less than 0.1 cfs. In Homestake Mining Company's Application for Mining and Reclamation Permit, Homestake acknowledged that "underground mining operations may have intersected drainage of the nearby Emperius Mine (aka Commodore Mine/Nelson Tunnel), causing diversion of that mine's non-tributary water decree" (Homestake Mining Company, 1977).

During the early 1990's, discharge from the Nelson portal averaged below 20 gpm, but steadily rose to around 300 gpm in 1999. A sudden increase in flow at the portal from 300 gpm to well over 480 gpm was observed during November of 1999. Flow remained relatively constant at over 480 gpm between November of 1999 and December of 2000, when flow subsided to approximately 280 gpm. Periodic discharge measurements between December 2000 and the present indicate fluctuations between 180 gpm and 330 gpm.

Flow measurements, as shown in Figure 13, conducted at the Nelson Portal, Nelson Tunnel at Bachelor Shaft and Nelson Tunnel near Noname Winze indicate that on average betweem 80% and 90% of the discharge from the Nelson Portal is coming from upstream of Noname Winze. This observation is confirmed based on the lack of additional discreet inflows between the portal and Noname Winze.

Figure 13. Flume installation at Noname.

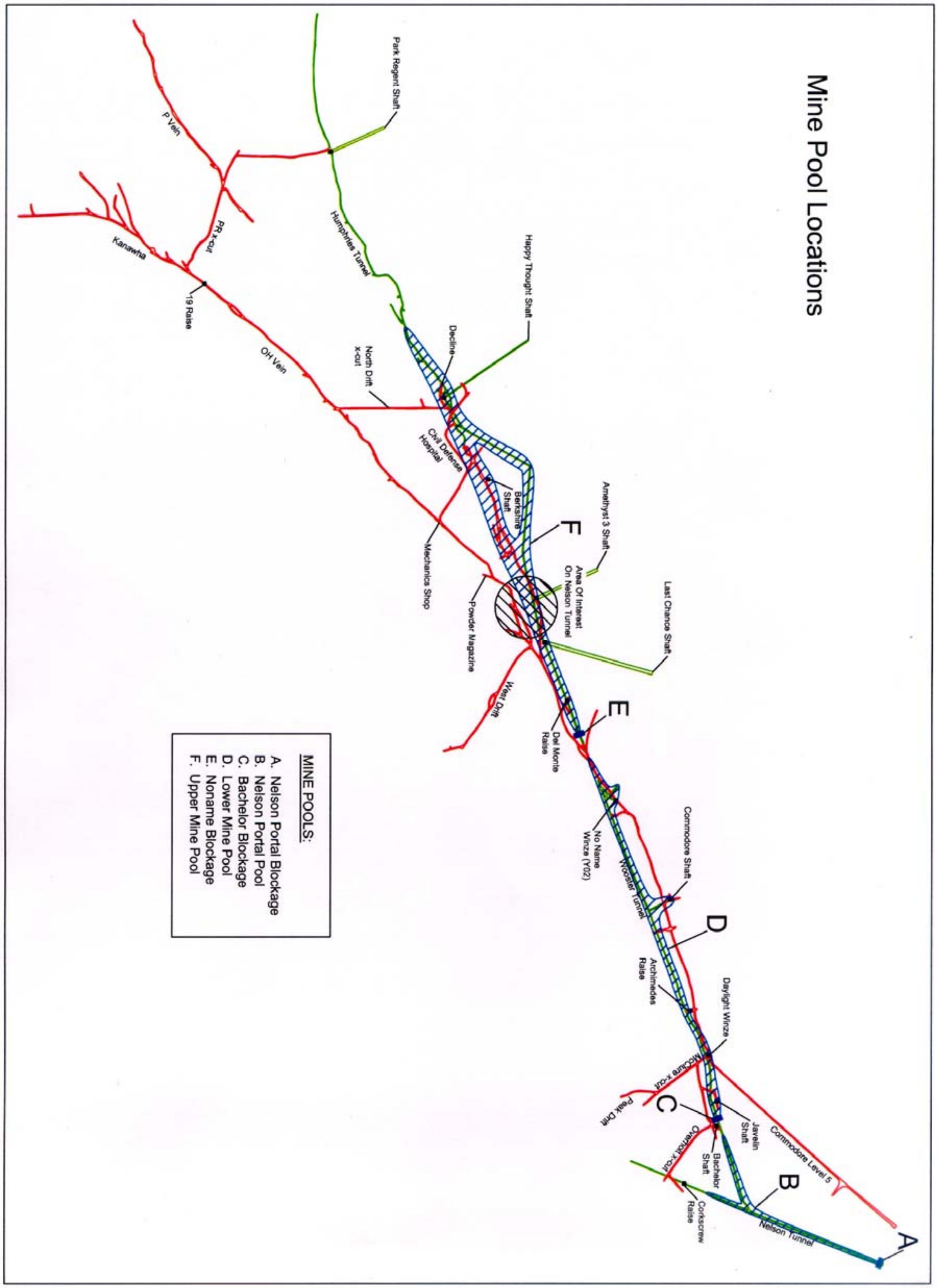

Figure 12. Mine pool locations.

Both water elevations of the mine pools and flow discharge at both the Nelson portal and Bachelor shaft fluctuate constantly. Due to the limited data set, discerning distinct correlations is difficult. Some fluctuations in mine pool elevation may result from new collapses impounding additional water or from the blowout of previous collapses. High water marks, noted by iron staining, indicate some mine pool elevations 8 to 10 feet higher than currently observed. The high flows of 2000 may have resulted from the blowout of a large impoundment within the mine. No obvious seasonality can be linked with flows or mine pool elevations, nor are the trends between mine pool elevations and flow measurements correlative with each other. To adequately gage water flow trends within the mine, a larger data set with more consistent measurements is necessary.

During 2001 a dye tracer study was conducted within the Commodore Mine complex by Cambrian Ground Water Company. As part of the study, florescent dye was added to the Berkshire Shaft and monitored for at the Nelson Portal. The study was designed to establish various flow parameters for water with the mine workings. Results of the study indicated that water moves through the mine workings from the Berkshire Shaft to the Nelson Portal, a distance of approximately 7300 feet, within 4.5 days (Davies, 2001). Some of the parameters established through the study are questionable due to the addition of dye to a stagnant pool instead of flowing water, and the effect of multiple mine pools on travel times. Regardless, it appears that water movement within the mine workings is relatively rapid.

<u>Water Quality and Isotopes</u>

Water quality data collected during the ongoing underground investigations is helping to establish baseline values and assist in the overall understanding of water migration through the mine workings. Collection of water samples at flowing sections of the Nelson Tunnel is limited to the Bachelor Shaft and above Noname Winze. Samples were also collected in pooled areas for water quality. Sampling of pools was conducted near surface and at depth, and indicated stratification of metals concentrations. Analysis of the current water quality data suggests that the majority of metal laden water is entering the mine workings upstream of Noname Winze. Loading analysis shows that 95% or more of the zinc, cadmium and lead load are coming from upstream of the Bachelor Shaft, while only 80% of the copper load is coming from above Bachelor. Determining exact loads above Noname is somewhat difficult considering previous flow measurements suggest substantial error. A reasonable assumption is that flow above Noname is 80%-90% of the flow above Bachelor. Based on that assumption and known metals concentrations, at least 80% of the zinc, cadmium and lead loads are coming from above Noname, while only 50% of the copper load is coming from above Noname. Other metals show interesting and complex geochemical relationships, but additional flow measurements and water quality data are needed to more thoroughly interpret the findings.

Temperature measurements of water within the mine suggest long residence times within the ground. Water temperatures ranged from around 10ºC (50ºF) to 19ºC (66ºF), with some of the highest readings recorded in the Nelson Tunnel above Noname. The majority of surficial water is derived from snow melt, and during midsummer, temperatures often range from around 4ºC to 8ºC. Mine water temperatures of 19ºC most likely indicate geothermal heating due to long residence time within the ground. Some heating may also occur due to the exothermic oxidation of pyrite within the pooled water of the mine workings.

An isotopic analysis of mine water was conducted in 2001, to determine possible sources to the mine drainage. Water samples were collected at the Berkshire shaft, the Peak Drift Borehole, Nelson Tunnel Portal and in Windy Gulch, and were analyzed for Tritium. Tritium is an isotope of hydrogen formed during atmospheric testing of nuclear weapons. Peak atmospheric testing of nuclear weapons occurred during the late 1950's and early 1960's resulting in a bomb spike, and allowing for the measurement of tritium values relative to that peak. Since most groundwater is a mix of multiple sources, absolute ages cannot be given by tritium numbers, instead, average values indicative of the individual components is derived. Samples collected and analyzed by Cambrian Ground Water Co. indicate that water discharging from the Nelson Tunnel "has the largest pre-bomb component" (Davies, 2001). The results suggest that the source feeding much of the Nelson Tunnel discharge is deep seated with either a long pathway from surface to eventual discharge and/or very slow velocities. Isotope analysis and temperature data appear to correlate well with the conclusion that much of the water discharging from the Nelson portal has been in the ground for a long time.

<u>Dewatering Project</u>

One of the final portions of the Nelson Tunnel that remains unexplored is the flooded portion of the tunnel above Noname Winze. This flooded portion of the Nelson Tunnel is the section of mine where the Amethyst, P, and OH veins appear to converge, and historic records indicate "big" water was encountered during mining. Determining the exact location and condition of water flow into the mine is a critical component of investigating potential source control. CDRMS put together a proposal to the WCRC regarding full scale dewatering of the Nelson Tunnel, but recommended implementation of a pilot scale project to determine full scale feasibility.

The dewatering proposal discussed various pumping locations, options for treatment of pumped water, infrastructure required for pumping, and conclusions. The recommendation of CDRMS to the WCRC was that dewatering from the Del Monte Raise using hydraulic powered pumps and subsequent treatment by lime and settlement in the West Drift met all the criteria for dewatering the Nelson Tunnel. The pilot phase of the project would involve completion of the necessary infrastructure to pump, treat, and transport water to the West Drift. After completion of the infrastructure, the West Drift would be filled to capacity (approximately 400,000 gallons). During this test, a number of variables associated with complete dewatering of the Nelson Tunnel could be better evaluated. Construction of the dewatering infrastructure was begun in 2004 and was only partially completed do to lack of funds. New funding received in 2006 will allow for the completion of the pilot project by late 2006. Full scale dewatering of the

Nelson Tunnel may never be financially or physically feasible, but the pilot project will likely result in useful data.

Source Control

The numerous underground investigations coupled with historic and geologic research are beginning to narrow and focus the potential source control options. So far the hope of finding discreet, manageable inflows into the mine has been unsuccessful. The flooded nature of the Nelson Tunnel has made determining the exact source and entry point of water into the mine workings very difficult. No high volume clean inflows have been discovered that would help in reducing the total volume needing to be treated at the portal. Implementation of inexpensive surficial hydrologic controls above the mine workings would likely be ineffective in reducing metal concentrations or discharge volumes at the Nelson Portal since local surface infiltration has limited impact. It appears that more large scale and expensive source control remains the only prospect.

The use of bulkheads to reduce or eliminate flow from the mine is a possibility. Watertight bulkheads could be placed at the Nelson Tunnel, Commodore mine levels 3-5, and the Amethyst 5 level which would allow water to fill the mine at least 700 feet above the Nelson Tunnel, and 500 feet below the surface. Historically, water discharge from the Amethyst vein was likely quite limited due to the alteration cap present near surface, and the lack of hydraulically conductive pathways. When the Nelson Tunnel was driven high volume flows that eventually tapered off were encountered at the Amethyst vein suggesting that water was pooled along the vein and subsequently drained. The use of bulkheads to block pathways created by mining could create near pre-mining conditions along the Amethyst vein, and allow for little or at least more diffuse discharge. Additionally, the water level could be raised above all sulphide ores therefore reducing oxidation and acid generation. The use of bulkheads is generally expensive, and often results in unforeseen consequences. Calculating and defining final mine pool elevations, discharge points and the effect on regional groundwater is difficult and uncertain. The use of bulkheads remains an option, but may not be prudent due to the expense and uncertainties.

If the exact pathways feeding the mine drainage could be determined, grout curtains or drawdown wells could be installed to prevent inflow into the mine. Generally, installation of grout curtains and drawdown wells is expensive, especially when considering that the workings are nearly 1400 feet below the surface. The possibility of installing flow prevention methods within the mine workings is feasible, but would also be expensive since very little of the necessary infrastructure for such a project is in-place. The biggest hurdle preventing the use of inflow controls is the uncertainty of the exact water pathways. The Amethyst vein appears to be the most likely pathway, but the OH and P veins could also be acting as conduits. There may also be an unknown pathway providing a large flow component. Determining the exact source and pathway of water will require dewatering the Nelson, or the introduction of tracers into the various veins through drilled holes. The use of tracers would probably be the least expensive, but would require drilling holes along vein to the water table from the Commodore 5 level or from surface. The use of inflow controls may provide the cheapest long term method of source control if the inflow pathways can be determined.

Treatment remains the most certain method of dealing with the Nelson Tunnel discharge. The difficulty with treatment near the portal is the lack of adequate space for ponds and facilities. Another major drawback is the initial and perpetual costs associated with treatment. A study conducted by McLaughlin Rincón Ltd. suggested an initial cost of around $2 million for facility and infrastructure construction with annual O&M costs of just over $100,000. One possible option that could be explored would be to drawdown the Bulldog Mine. During operation of the Bulldog Mine, dewatering resulted in the reduction of Nelson Tunnel discharge to less than 40 gpm. Currently the Bulldog mine has been reclaimed and the mine pool has risen substantial since the cessation of dewatering. Treatment of the pumped water would be required at the Bulldog, but construction of the infrastructure would likely be easier and cheaper. Various unknowns regarding dewatering of the Bulldog mine pool exist that might eliminate the possibility. Additionally, reaching an agreement with the Bulldog owners regarding facility construction and subsequent treatment could be difficult. One option that should be explored is the possibility of some form of underground treatment. A sequence of bulkheads could be constructed that would serve as settlement ponds, and lime or other neutralizing agent could be added remotely from the surface. Additional investigations should be conducted to establish the feasibility of this option. Some form of treatment remains the most certain option, but likely one of the most expensive and involved.

There may be other source control options that could become feasible or obvious based on continuing investigations of water pathways within the mine workings, or through technological advancements.

Conclusions

Investigations of history, geology and existing conditions underground have led to a more comprehensive understanding of the potential for source control. Cooperation between local stakeholders, state agencies and federal agencies has allowed for much of the underground investigation to take place, while facilitating analysis by individuals and agencies with varying areas of expertise. Much of the investigative work completed so far should be viewed as beyond preliminary, but certainly not exhaustive. Ongoing monitoring of hydrologic conditions within the mine will facilitate a better understanding of "what's really going on" versus speculation and hypothesis. The potential for utilizing source control to eliminate or reduce discharge at the portal may prove difficult or impossible based on the data collected so far. Additionally, implementation of source control will likely be very expensive. The collection of additional data and analysis will continue to clarify the feasibility of source control implementation.

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